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From waste to fertilizers: integration in the Circular Economy and Sustainability

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Abstract: An attributional life cycle analysis has been carried out to evaluate the integration in the circular economy and sustainability of digestate from anaerobic digestion (AD) in its use as an organic fertiliser (or biofertilizer), as well as comparing the obtained environmental impacts with those of the inorganic fertilisers which are currently used. To this end, a life cycle analysis of the biofertilizer that could be obtained after the anaerobic digestion of organic waste from the 23 largest food markets in Spain has been carried out. For this purpose, the biofertilizer production process was modelled for each of the 23 markets in the LCA software Simapro. The obtained results were then analysed to find out the difference in environmental impacts according to waste quantity and quality, for which it was established that the mix of meat, fish or vegetable quantity does not impact the results obtained for the 11 impact categories that were studied. Additionally, the obtained impacts were compared to those of inorganic (NPK) fertilisers of the same composition to determine the environmental impact reduction that would happen if the biofertilizers were to replace their inorganic competitor. An average 55% reduction of overall environmental impact was achieved across the 23 food markets thus, concluding that digestate biofertilizers are a more sustainable option for soil fertilization.

Keywords: Organic fertilisers; LCA; Circular Economy; Mercasa; Sustainability; Anaerobic digestion; organic waste

1. Introduction

The European Union is currently in the midst of searching for and developing renewable energy sources to replace the fossil resources used to date, as well as struggling with the increasing amount of waste generated by its population. In this context, anaerobic digestion (AD) presents an opportunity not only for energy transition, but also for the development of local economies and progress in the implementation of the concept of circular economy in society. Another advantage of AD is that it produces a waste product called digestate, an organic sludge rich in nutrients. This digestate contains the same nutrients that enter the digester, making it a very rich organic fertiliser, the use of which reduces the need for chemical fertilisers and promotes soil sustainability.

It is precisely this last aspect of DA that motivates this study: the use of digestate as a vector of circular economy through its application as a biofertilizer. This concept is not new, however, few studies have focused on the comparison of environmental impacts between common (inorganic) fertilisers and those derived from digestate, as well as the savings in raw materials and fossil resources that replacing fertilisers with digestate entails. Throughout this study, the production process of the biofertilizer derived from digestate will be analysed in depth to carry out a Life Cycle Assessment (LCA) of the same and compare it with LCAs of NPK type inorganic fertilisers (those used in most current crops). As the properties and environmental impacts of digestate depend mainly on the type of waste treated in the AD, and to be able to use relevant data for the Spanish industry, separate LCAs will be carried out for the specific quantity and composition of the different organic wastes generated in each food market in Spain.

2. State of the Art

In a global context where the search for sustainable solutions has become a priority, life cycle assessment and circular economy emerge as fundamental approaches to assess the environmental impact of production systems in a standardized way [1-3]. LCA methodology has already been applied to anaerobic digestion and biogas generation. For instance, [4] studies the environmental impacts of the AD of the organic fraction of municipal solid waste, and [5] compares the environmental impact variation depending on the type of organic waste entering the digester, concluding on a better environmental efficiency for smaller manure digesters over large, energy crop digesters. However, most LCAs concentrate on evaluating the environmental impacts of biogas production, but very few contemplate digestate as a potential subproduct for biofertilizer manufacture by adding the necessary posttreatment processes [6]. Therefore, in light of the growing importance of sustainable solutions and the current focus on life cycle assessment and circular economy principles, this study aims to address the significant research gap by specifically exploring the potential of digestate from food waste as a valuable subproduct for biofertilizer production through appropriate posttreatment processes.

3. Objectives

The final objective of this project is to quantify the level of integration in the circular economy of the use of digestate as a biofertilizer for agricultural crops, thus replacing the fertilizers currently used. In order to quantify it, a Life Cycle Analysis (LCA) of the digestate as a biofertilizer is carried out from the organic waste generated at the biggest food markets of the country. To achieve this objective, certain previous steps must be fulfilled according to the following order:

- Establish scope and goal LCA to be carried out: system boundaries, functional unit and impacts to be analysed. These are the fundamental parameters that limit the scope of the study both upstream and downstream of organic fertilizer production, as well as the magnitude and unit to which all the results of the study will refer. It is also very important to define what environmental impacts are going to be analysed, to ensure that the correct information is provided to the LCI (life cycle inventory).
- Elaboration of the LCI: consists of determining all the processes to be taken into account in the impact inventory, as well as all the raw materials, products, by-products and their residues. For this phase it will also be necessary to analyse the waste entering the digester in each market (its quantity and composition), as these will determine the quality of the digestate and, consequently, the quality of the biofertilizer.
- Life cycle impact assessment (LCIA). Once the inventory has been completed, the LCA results are obtained through the CML method. These results will first be analysed separately at the different stages of the process to adjust the model if necessary. Subsequently, the results obtained for different markets will be compared to analyse the impact of the quality (organic waste mixture) of the waste at the digester inlet.
- Sustainability inclusion analysis. The results obtained for the 23 biofertilizers in the food markets are compared with inorganic fertilisers of the same composition, to quantify the savings in environmental impacts of using biofertilizer instead of inorganic fertiliser.

4. Materials and Methods (Methodology)

The following sections detail the LCA methodology applied to the 23 digestate biofertilizers produced by each of the studied food markets:

4.1. Goal and Scope of the LCA

The goal of this LCA is to obtain the environmental impacts of organic fertiliser production from anaerobic digestate digestion, while the scope of this LCA encompasses digestate originating from different waste mixtures and in different amounts, in order to also analyse the variability of the results depending on the substrates used in the anaerobic digestion process.

4.1.1. Function and Functional Unit

The LCA to be carried out in this project is an attributional LCA, i.e., it will try to represent the biofertilizer process in isolation from the rest of the economy and establish clear limits beyond which its impacts are no longer considered. All the impacts obtained after the inventory assessment are referred to the functional unit, which is 1 kg of biofertilizer produced from digestate at the end of the production process.

4.1.2. System Boundaries

Figure 1 shows a graphical representation of the system boundaries that limit which environmental impacts must be considered in the LCA framework. For the biofertilizer process, the system boundaries are upstream, the input of organic waste to the digester, and downstream, the production of biofertilizers. The objective of this study is to compare the production impacts of biofertilizer and common inorganic fertilizer, so the life cycle analysis inventory ends with the production of these products, and the impact of these products after their application will not be analyzed. It is also important to highlight that only digester operation flows will be considered, and recharge activities (digester cleaning and micro-organism substrate recharge) will be disregarded. No transport of organic waste from the food market to the digester will be envisaged either, as the digester is assumed to be on the market's own premises. The digestate will not be transported for post-treatment either, as this will be done on site.

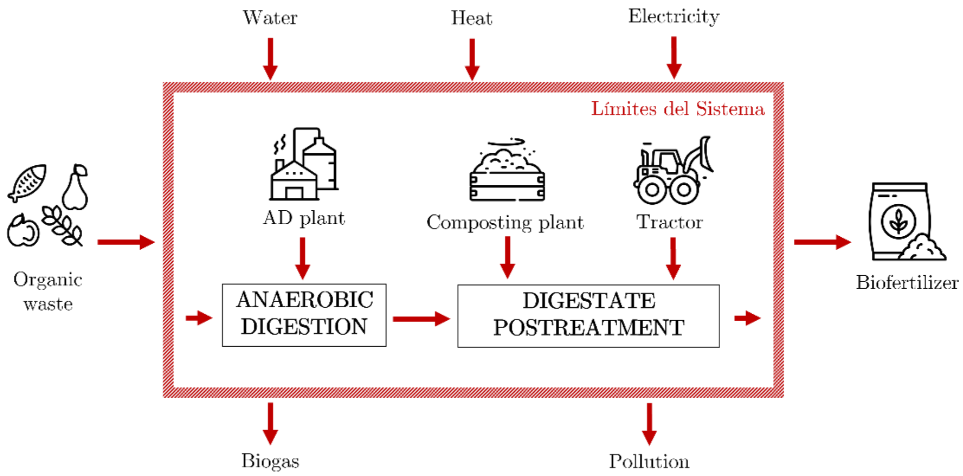

Figure 1. *System boundaries of the proposed LCA*

Regarding the infrastructure used during the process, the anaerobic digestion plant and digester and the composting plant will be considered. To inventory the impacts corresponding to the infrastructure per kg of biofertilizer produced, its total construction and operation impacts will have to be added and divided by the amount of waste treated over its lifetime. Finally, only air emissions from the AD and posttreatment processes will be considered in this study. At all times it is assumed that anaerobic digestion of waste and post-treatment of digestate is carried out in approved plants with soil leakage prevention devices and wastewater treatment equipment, which prevent any emission of pollutants to soil and local waters.

4.2. Life cycle inventory (LCI)

The inventory of an LCA is where all the processes that are necessary for the elaboration of the functional unit, and that are included within the limits of the system, are compiled. Below, Figure 2 shows the structure of the inventory established for this study, according to the levels of importance of the production flows of the processes involved in obtaining the biofertilizer.

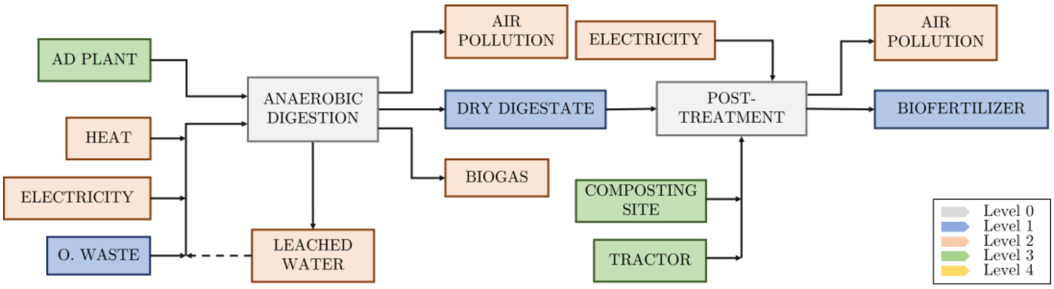

Figure 2. *Life cycle inventory structure*

To simplify the identification of unit flows, the inventory of the LCA has been divided into two main processes: anaerobic digestion of organic waste and post-treatment of digestate. The flows attributed to each process are explained below:

4.2.1. Anaerobic digestion (AD)

Anaerobic digestion is a biological process in which microorganisms break down incoming organic matter in the absence of oxygen, consisting of 4 main stages: hydrolysis, acetogenesis, acidogenesis and methanogenesis [7]. After this process, the incoming organic waste is transformed into hydrogen, methane, and carbon dioxide, accompanied by digestate: the stabilised solid and liquid matter that could not be transformed into biogas. The process flows considered for the LCA inventory are as follows (a brief explanation of each flow is given below, and concrete quantities and qualities of each are analysed in the study for each of the 23 cases treated):

Organic waste issued from the food markets

The organic waste is the main input of the anaerobic digester. For each of the markets, the waste assigned is the real quantity and mixture of organic waste (meat, fish, vegetables, and fruit) that is produced annually at the 23 largest food markets in Spain [8].

Additional water to control the pH of the process

Generally, it is necessary to add water to the digester to raise the humidity of the incoming waste, as well as to regulate the pH and temperature of the digester. General practice in the industry points to the recirculation of liquid digestate as the optimal method for water provision ([9]), but it is performed differently according to the type of organic waste processed. After performing a literature review on the liquid digestate recirculation practices for different substrates of AD ([10,11]), a recirculation of 30% of the liquid fraction of the digestate has been established.

Process infrastructure

A standard digester is dimensioned for all 23 cases. To obtain the environmental impact of the anaerobic digester and the auxiliar infrastructure (also called infrastructure amortization), it is necessary to add up all construction and operation impacts of set infrastructure during the complete life cycle and divide it by the total amount of biofertilizer produced during the same period, thus obtaining the derived impacts for producing 1 kg of fertilizer.

Heat and electricity provided to the process

Currently, anaerobic digesters are oriented towards energy self-sufficiency, which means that a part of the biogas generated is used as fuel for the plant's electricity and heat needs while the surplus is considered as the net energy produced by the system [12]. For each market, the heat and electricity needs are calculated using the hypotheses presented in [13], for its specific quantity of organic waste and using a standard organic digester of 4,613 m^3.

Biogas produced in the digester

The amount of biogas produced in each of the 23 studies cases has been calculated based on the experimental data in [13], for which the biogas production and composition of different organic food waste (meat, fish, vegetables, and fruit) are provided.

Digestate exiting the digester

The used digester quantity and composition has been established according to the experimental data provided in [13], to which the 30% reduction of the liquid fraction was applied for water recirculation purposes.

Air emissions of the AD process

The process used is considered to recover all gases leaving the digester for use as biogas. However, any biogas leakage from the process at all stages is considered as emissions, for which the quantities given in [14] have been used.

4.2.2. Posttreatment: composting

The digestate resulting from AD has considerable moisture content and is not yet in optimal condition for use in soils, so it is subjected to a composting process: a biological, aerial and controlled technique of stabilisation and treatment of biodegradable organic waste, both solid and semi-solid. As with the AD process, the following process flows have been tailor-made for each of the 23 cases studied.

Digestate exiting the AD process

As described in the previous section, the digestate exiting the digester’s quantity and composition has been established according to the experimental data provided in [13], to which the 30% reduction of the liquid fraction was applied for water recirculation purposes.

Process infrastructure

The same procedure used in the infrastructure of the AD plant impacts is applied: all construction and operation costs throughout the plant’s lifecycle are divided by the total production of biofertilizer, thus obtaining the environmental amortization of the composting plants.

Use and amortisation of digestate aeration machinery (tractor/shovel)

In composting, it is necessary to stir the substrate frequently to provide oxygen to the microorganisms in the process. This aeration is carried out with a diesel-powered mechanical shovel, the amortisation, and emissions of which depend on the amount of digestate treated.

Air pollution of the composting process

The atmospheric emissions produced by composting per amount of digestate treated have been established according to the emissions set by the Ecoinvent library for composting processes. Since composting is generally carried out in open facilities, all these generated emissions are emitted into the atmosphere.

Biofertilizer produced after composting process

For each market, a mass balance of the composting process has been carried out, thus obtaining the amount and composition of the resulting biofertilizer.

Once the quantities and qualities of each process flow have been detailed according to the market to be analysed, the life cycle inventory has been built in Simapro, according to the structure presented in Figure 2.

5. Results and Discussions

Once the inventory of the LCA has been constructed, the impacts associated with it have been calculated according to the CML method. The CML method, a methodology created by the Institute of Environmental Sciences of the University of Leiden in 1992, quantifies the environmental impact of processes in 11 impact categories: depletion of abiotic resources, depletion of fossil resources, contribution to climate change, ozone layer depletion, human, marine, freshwater and terrestrial toxicity, photochemical oxidation, acidification and eutrophication.

The results of the study contain, in a first phase, the quantification of the 11 impact categories for the 23 cases studied, followed by a sensitivity analysis of the of the infrastructure dimensioning impact. In a second phase, and with the aim of evaluating the sustainability of the biofertilizers, the results are compared with those of LCA of inorganic fertilizers of the same composition.

5.1. General results

After obtaining the raw results for each of the 23 cases, a comparison by impact category has been made to assess how the differences between organic waste qualities and quantities affect the results. Figure 3 represents the results obtained for the category of contribution to global warming potential, measured in CO_2 equivalent emissions (the analysis of the other 9 impact categories is shown in the study).

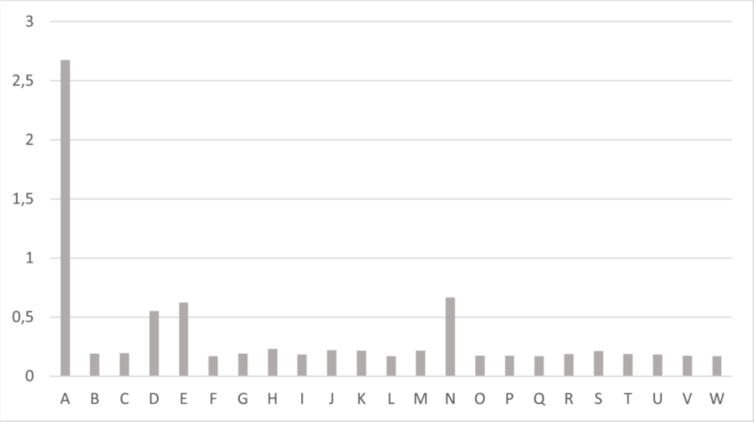

Figure 3. *Results for global warming potential (kg CO_2 eq.) for all food markets*

As can be seen in Figure 3, there are 4 different levels of results, which depend mainly on the amount of organic waste and the design of the infrastructure used in the study, and which are repeated for the other impact categories. Global warming potential of market A is up to 11 times higher than that of the other markets. This result is due to an oversizing of the anaerobic digestion infrastructure, causing a higher infrastructure amortization impact per kg of biofertilizer produced. The same phenomenon, although on a smaller scale, occurs in market B, which also shows anomalous results.

Also noteworthy is the impact of the under sizing of infrastructure that occurs in markets E and N, which, due to the large influx of waste from food markets, does not generate enough biogas for anaerobic digestion to be self-sufficient. A priori, they present a lower proportional impact of infrastructure, which would have given a better result. However, the impacts derived from the fossil proportion of the national electricity mix contribute an equivalent CO_2 that triples the results of the other markets. At a lower level we can find the remaining 19 cases, which present the same results except for small differences in sizing.

5.1.1. Sensitivity of the results to infrastructure sizing

In view of the impact on the results observed due to the over or undersizing of infrastructure, a sensitivity analysis of the results obtained for the 11 impact categories has been carried out, analysing the results obtained if the infrastructure is excluded from the processes, and the impact per impact category that these have in each of the 23 cases.

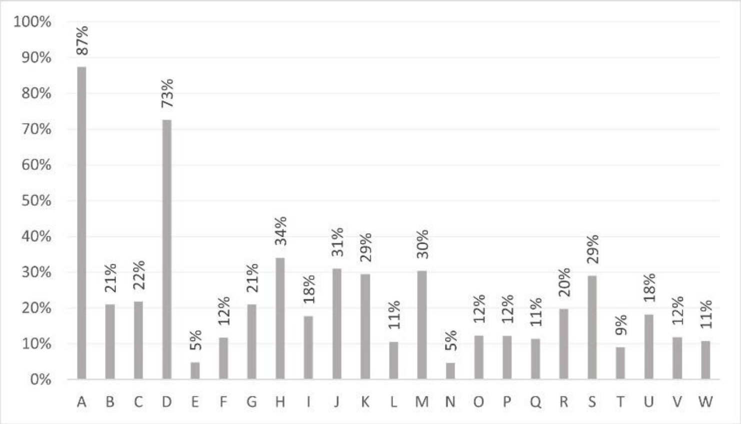

Figure 4. *Percentage of results derived from the infrastructure for global warming potential (kg CO_2 eq.)*

Figure 4 clearly shows the percentage of infrastructure-only derived impacts in the category of global warming potential, where it can be clearly seen that infrastructure alone makes up almost the total impact obtained for markets A and D and only 5% for markets E and N. This phenomenon occurs, albeit at different scales, in the rest of the impact categories studied, and it validates the hypotheses that were formulated in the first stage of the interpretation of results.

In order to eliminate result variability due to infrastructure impacts, it would be necessary to properly size each anaerobic digester according to the annual organic waste influx that it receives. This fit dimensioning would then stabilise the percentages of Figure 4 into a standard infrastructure impact across all 23 markets.

5.1.2. Result analysis excluding infrastructure impacts

In light of the overall result distortion caused by the imposition of a standard infrastructure across all 23 food markets, a third stage of results analysis excluding the impacts derived from infrastructure has been performed, which is represented in Figure 5. Figure 5 shows that, once the infrastructure impacts have been removed, all food market score the same results except from those that are not self-sufficient (i.e., don't produce enough biogas to cover their electric and heat demand).

The extra potential for global warming observed in these four markets is directly derived from the environmental impacts of the Spanish electricity mix (the non-renewable part) from which they source their electricity and heat needs. Moreover, it can be observed that the final score in this category is directly proportional to the amount of electricity demanded form the grid, as market N demands 16 more times the energy that market T imports from the grid for each kg of biofertilizer produced.

It is also interesting to note that the remaining 19 markets have almost the same result for this category. This is because, by eliminating the oversizing of the infrastructure and using a functional unit of 1 kg of biofertilizers to reference the results to, the only differentiating factor between the different markets is the mixture of meat, fish, fruit and vegetable waste at the inlet of the anaerobic digester. As all these types of organic wastes are considered as a waste in the life cycle inventory, the LCA methodology assigns them a null environmental impact upstream, thus having no impact on the results of the environmental impact assessment. This makes the amount of biogas produced by each market the only differential factor between the obtained results of the different self-sufficient markets.

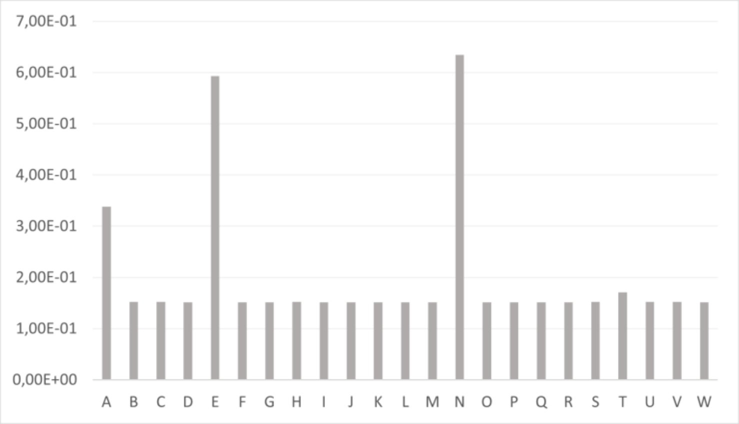

Figure 5. *Results for global warming potential (kg CO_2 eq.) excluding infrastructure impacts*

5.2. Comparison of the results of biofertilizer LCA to inorganic fertilizers

To be able to fairly compare the biofertilizer with the commercial fertilisers generally used in agriculture, and thus to be able to evaluate them as a sustainable alternative, it is necessary that they have the same composition (as a difference in composition can result in a substantial difference in the results of the LCA). For this reason, each biofertilizer will be compared with an NPK fertiliser (containing nitrogen, phosphorus, and potassium) of the same composition. It is important to note that these inorganic fertilisers have tailor-made compositions to compare them correctly with the biofertilizer on the markets, but none of them has an inorganic fertiliser composition that is common in agriculture. In the future, to obtain a biofertilizer composition to replace common fertilisers, it will be necessary to vary the percentages of each substrate at the input of the AD process.

Four of the studied markets will be analysed as representative cases. For each of them, the impact of the inorganic fertiliser on the impact of the biofertilizer will be analysed so that, if a score higher than 100% is obtained, the biofertilizer has a lower impact than the commercial (inorganic) fertilizer.

The results are presented as a coefficient of total inorganic fertiliser impact divided by total biofertilizer impact thus, meaning that there is an environmental impact reduction in the biofertilizer when the score of the bar is above 100%.

Market A

This case represents the phenomenon of infrastructure oversizing that has been observed in the analysis by impact categories, as well as being one of the markets that is not self-sufficient in the anaerobic digestion process. The oversizing can be easily appreciated in the poor coefficient obtained in the abiotic depletion category (15%), which involves most of the infrastructure-related impacts while the effects of not being self-sufficient and using non-renewable energy to operate are clearly represented by the low scores in the fossil fuel depletion and global warming potential categories. Overall, it can be seen the great impact of this oversizing, since Figure 6 shows that the commercial fertiliser outperforms the biofertilizer in all impact categories of the CML method, concluding that biofertilizer is, in this case, less sustainable than a common inorganic fertilizer.

Market D

This market again has a much larger infrastructure than necessary, although, in this case, the volume of waste it gets is sufficient to generate the heat required by the digester, so it does not require energy from the electricity grid. Again, the oversizing is clearly represented by a biofertilizer that has twice the abiotic depletion impact than the inorganic fertilizer. By being self-sufficient, the results obtained in the remaining impact categories are considerably improved (Figure 7), resulting in a biofertilizer that is competitive in the categories of fossil fuel depletion and ozone layer destruction, as well as getting overall better results than the previously analyzed market A.

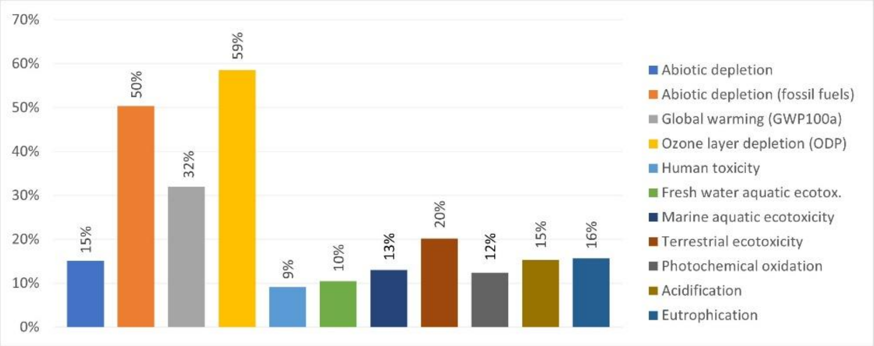

Figure 6. *Results comparison for biofertilizer and inorganic fertilizer for market A*

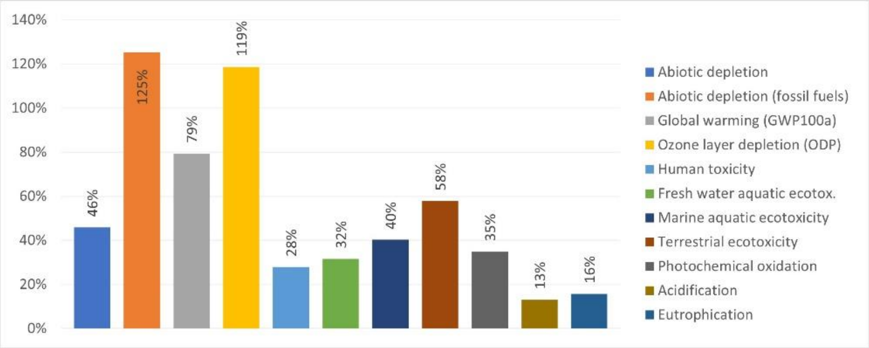

Figure 7. *Results comparison for biofertilizer and inorganic fertilizer for market D*

Market G

This case is the standard case, as it represents the remaining 19 markets in that it does not present problems of over-sizing or self-sufficiency, as well as using varied organic waste at the origin of the production process. This is the best possible case, as it reproduces the real conditions of a digestate biofertilizer coming from an AD plant correctly dimensioned for the incoming volume of waste, thus allowing a comparison on equal terms with the inorganic fertilizer. Figure 8 shows how biofertilizer improves the results of organic fertiliser in 9 of the 11 impact categories analysed and, in many of them, being up to several times more sustainable (exceeding 100% impact reduction). The category that shows the most reduction is abiotic depletion (86% of reduction), as producing a fertilizer from organic waste avoids the need of using up natural resources to obtain nutrients such as potassium, nitrogen or phosphorous. Additionally, the fact the AD process is self-sufficient and does not bring any impacts derived from the fossil fuels used in the national electric mix (mostly the absence of coal-produced electricity) lower significantly the toxicity to human lives (75%), aquatic (80%) and terrestrial ecosystems (81%).

It is important to highlight that none of the 23 market present an impact reduction in the categories of acidification and eutrophication. This phenomenon is mostly linked to the ammonia emissions that take place during the composting process, and which do not suffer any control or filtering before being directly emitted to the atmosphere. The nitrogen present is this ammonia is then directly responsible for the lack of environmental competitivity in these categories.

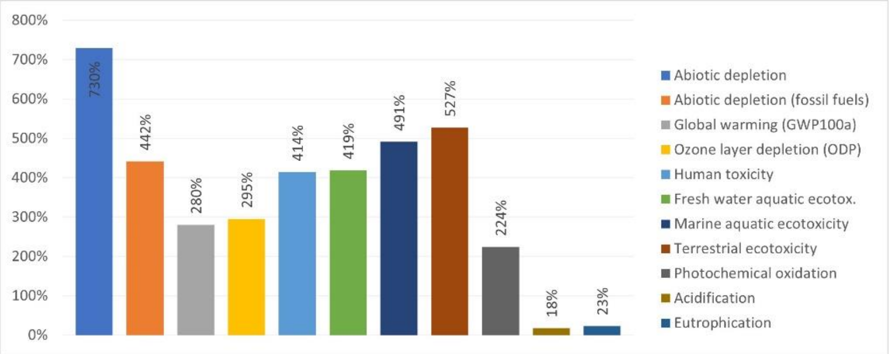

Figure 8. *Results comparison for biofertilizer and inorganic fertilizer for market G*

Market N

Market N, as well as market E, presents the opposite case to market A: an undersizing of the infrastructure. This market generates too much waste for the established digester size, so not enough biogas is generated for the high energy demand of the digester. A priori, this undersizing should improve the results with respect to the typical case (as can be seen in the large natural resource depletion result, with an impact reduction of 92%), as the impact of the infrastructure per kg of biofertilizer is considerably reduced, but the energy required from the grid means adding the impacts of the national energy mix, increasing the results for all categories. It is for this reason that Figure 9 has an average result that is better than market A, but not reaching the 9 improved categories of the typical case (market G).

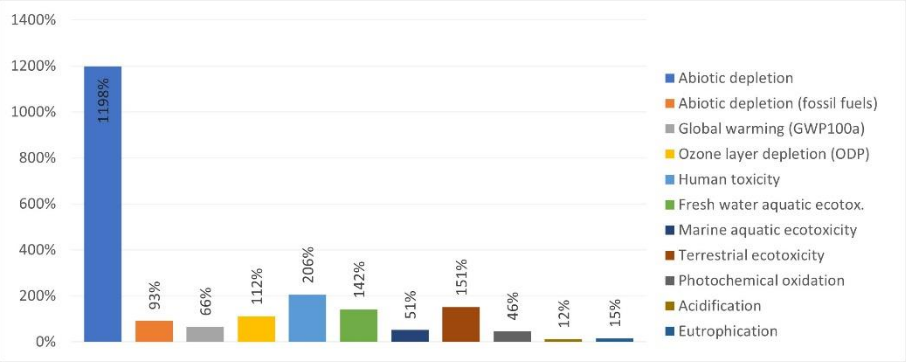

Figure 9. *Results comparison for biofertilizer and inorganic fertilizer for market N*

The dependence on the national grid for the digestate production is easily appreciated in the fossil fuel depletion and global warming categories where, despite the offset produced by the great undersizing of the infrastructure, the biofertilizer has greater impacts that the respective inorganic fertilizer.

7. Conclusions

Throughout the study, the construction of the biofertilizer production model has been detailed, as well as its environmental evaluation compared to the current alternative: inorganic fertilisers. For this purpose, inorganic fertilisers of the same composition as the biofertilizer obtained for each of the 23 markets studied through a process of anaerobic digestion and standardised compost have been chosen.

The results of this comparison vary substantially depending on the volume and composition of waste in each case, as well as the environmental category in which the comparison is made. To be able to definitively compare the results obtained for fertiliser and biofertilizer (and thus determine which of them is better, environmentally speaking), the scores for each of the categories have been converted to unit values, thus obtaining an aggregated total score for each product. Figure 10 below shows for each market the relative savings in environmental impacts of biofertilizers compared to an inorganic fertiliser of the same compostion.

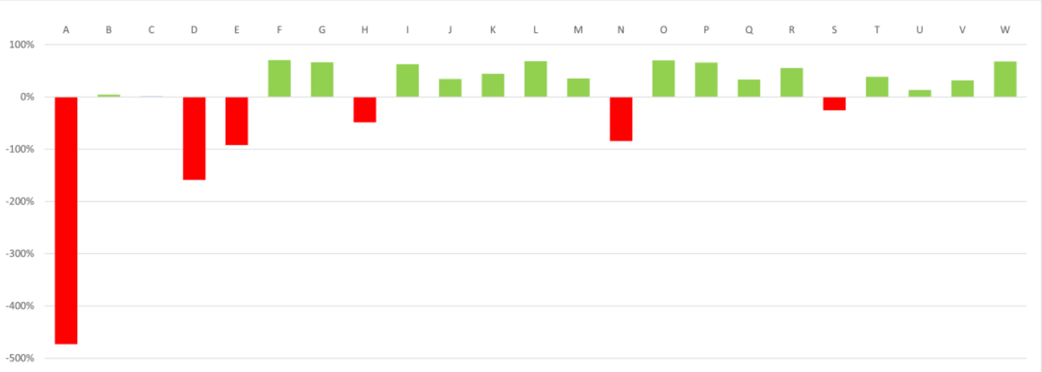

Figure 10. *Unit comparison between fertiliser and bio-fertiliser for the 23 markets*

In the light of the results shown in Figure 10, 75% (17 out of 23) of the studied cases led to a reduction of the total environmental impacts of their comparator fertiliser. The following cases stand out negatively:

- Market A, due to the oversizing of the equipment, which makes the impact of infrastructure sizing, and the process' energy demand from the grid.
- Market D, due to the oversizing of the infrastructures, although better than market A as the process is self-sufficient.
- Markets N and E, due to the undersizing of the infrastructure in relation to the volume of waste treated, making the process dependent on the electricity from the grid.
- Markets H and S, whose waste mixture contains only vegetables, and due to slight infrastructure oversizing.

In the remaining 17 cases, an average saving of 55% of the impacts of conventional fertiliser is obtained, thus demonstrating that biofertilizer is a more sustainable alternative for providing nutrients to soils in agriculture, as well as being an effective method of recovering a by-product (digestate) of an AD process that already recovers waste from various food markets.

7.1. Future Improvements

The biofertilizers production process model used in this study is a first approximation to the evaluation of biofertilizers as a substitute for inorganic fertilisers. Throughout the simulation and analysis of the results, a series of limitations of the model have been found which, although they allow its scalability, affect the accuracy of the results it provides. The improvements to be incorporated in a second iteration of the process model are listed below:

AD process modelling

Throughout the results analysis, the impact of using a standard infrastructure for all markets has been observed in the life cycle analysis results: oversizing of infrastructure leads to a higher building impact per kg fertilizer, and undersizing to a lower impact. The results sensitivity to infrastructure dimensioning is considerable, and in the cases where the standard infrastructure is not adjusted to the volume of waste treated, it always results in a more polluting biofertilizer than its conventional inorganic counterpart. Further iteration of the study should adapt the infrastructure's size to waste quantity so this sizing factor can be eliminated.

Additionally, in the model used in this study the mix of substrates to be digested only has an impact on biogas production and biofertilizer composition. However, the mix of substrates in the digester or co-digestion can be a key factor in optimizing biogas production, thus reducing the percentage of impacts attributed to the digestate and, therefore, reducing the final impact of the biofertilizer. It would be of great interest to optimize the waste mix available in each market to optimize the biogas generated, and to try to make all anaerobic digestion plants self-sufficient.

Posttreatment process modelling

In the current model, a standard life cycle inventory compost model provided by the Ecoinvent database, which sets a quantity of emissions of NH_3, H_2S, CO_2, NO_2 and CH_4 per kg of digestate composted. This first approximation fulfils the objective of characterizing the emissions and impacts derived from composting but does not take into account the composition of the digestate that is composted, which is a key factor in the amount of atmospheric emissions. To make the model more complete, it would be necessary to investigate the specific emissions as a function of the composition and composting time of the substrate.

LCA Scope and Boundaries

In the current model, a 'from cradle to gate' life cycle analysis is carried out, which means that all the impacts of raw material extraction, material processing and product manufacturing have been analyzed and accounted for, but the impacts of their use and final disposal have not been considered. To be able to evaluate in a more complete way both inorganic fertilizer and biofertilizer, it would be necessary to study the impact they have on soils once they are applied in terms of their composition, decomposition, and end of life, thus transforming the LCA to an LCA "from cradle to cradle".

References

1. DTU Library. *LCA history*. Available Online: https://orbit.dtu.dk/en/publications/lca-history
2. Martin Sastre C. Life cycle assessment and footprints course notes. *Universidad Pontificia Comillas (ICAI)* **2023**
3. Ellen MacArthur Foundation. *What is circular economy?.* Available online: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview
4. Ardolino F. et al. Biowaste-to-biomethane or biowaste-to-energy? An LCA study on anaerobic digestion of organic waste. *Journal of Cleaner Production* **2018**, vol 174, 462-476.
5. Bacenetti J; Sala C.; Fusi A.; Fiala M. Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. *Applied Energy* **2016**, vol 179, 669-686.
6. Angouria-Tsorochidou E. Life cycle assessment of digestate post-treatment and utilization. *Science of Total Environment* **2022**, vol 815, 192-204.
7. Morales Polo, C. Solid waste management course notes on anaerobic digestion. *Universidad Pontificia Comillas (ICAI)* **2023**
8. Mercados Centrales de Abastecimiento S.A. *Mercasa informe anual 2021*. Available online: https://www.mercasa.es/publicaciones/informes-anuales/.
9. Manu, M. A review on nitrogen dynamics and mitigation strategies of food waste composting. *Bioresource Technology* **2021**, vol 334.
10. Resch C.; Braun R.; Kirchmayr R. The influence of energy crop substrates on the mass-flow analysis and the residual methane potential at a rural anaerobic digestion plat. *Water Science* **2008**, vol 57, 73-80.
11. Zehui Z. Achieve clean and efficient biomethane production by making between digestate recirculation and straw.to-manure feeding ratios. *Journal of Cleaner Production* **2020**, vol 263.
12. De Sanctis S.; Chimienti C.; Oastore C.; Piergrossi V.; Di Laconi C. Energy efficiency improvement of thermal hydrolysis and anaerobic digestion of Posidonia oceanica residues. *Applied Energy* **2019**, vol 252.
13. Morales Polo C.; Cledera Castro M.d.M.; Hueso Kortekaas K.; Revuelta Aramburu M. Anaerobic digestion in wastewater reactors of separated organic fractions from wholesale markets waste. compositional and batch characterization. energy and environmental feasibility. *Science of the Total Environment* **2020**, vol 726.
14. Bakkaloglu S.; Lowry D.; Fisher R.; Frand, J. Quantification of methane emissions from UK biogas plants. *Waste Management* **2021**, vol 124.